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Helmet- and Head-Mounted Displays and Symbology Design Requirements

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Helmet-mounted display symbology for automated nap-of-the-earth rotorcraft flight

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ABSTRACT

Helmet-mounted display (HMD) symbology for an automated Nap-of-the-Earth (NOE) guidance and control system is described. In the automated system, referred to as Pilot-Directed Guidance (PDG), pilot control inputs are interpreted as high-level velocity commands to an inner-loop guidance and control system that is responsible for obstacle detection and avoidance maneuvering. The success of the PDG concept has been shown to be highly dependent upon the intelligent use of inertially stabilized symbology to provide navigational information and velocity command feedback to the pilot. Individual symbol functions and drive laws are described along with the associated display difficulties encountered at NOE airspeeds and altitudes. The important findings of a fixed base simulation experiment, relating to the use of HMD symbology, are given along with pilot commentary and opinion.

1. INTRODUCTION

Very low altitude Nap-of-the-Earth (NOE) rotorcraft missions require pilots to perform unique guidance and control tasks that typically include real-time navigation along with terrain and obstacle avoidance. The requirements of maintaining situational awareness, performing flight-path planning, and executing precision maneuvers often lead to excessive cockpit workload. Flight tasks are further complicated by low visibility and high auxiliary workload conditions. State-of-the-art sensor technologies that include infra-red and image-intensifying equipment have expanded the operational envelope for NOE flight missions. With these systems, however, the pilot must still perform the often formidable tasks of processing sensor information and making rapid, accurate control decisions. In an aim to further alleviate pilot workload and increase mission safety, a system for terrain and obstacle avoidance has been developed at NASA Ames Research Center that couples real-time sensor information with automated guidance and control. In the system, referred to as Pilot-Directed-Guidance (PDG), pilot control inputs are used to establish a high-level velocity command input to an inner-loop guidance and control system, as shown schematically as in Fig. 1. The inner-loop automation is responsible for obstacle detection and avoidance, terrain clearance altitude tracking, and airspeed hold. An important characteristic of PDG is that it provides flight-path autonomy to the pilot by not requiring that a fixed nominal waypoint course be followed. For missions at NOE altitude, previous simulation studies have shown that considerable apprehension is expressed by pilots asked to fly merely as system monitors of fully automatic, waypoint following systems.[1]

It is clear from simulation that pilot acceptability of automated NOE systems is highly dependent upon the specifics of the pilot-vehicle interface. It is equally clear that the pilot interface can be greatly enhanced by the intelligent use of available Helmet-Mounted Display (HMD) technology. The presentation of inertially stabilized symbology on an HMD has been successfully demonstrated in flight test for low-altitude terrain-following and terrain-avoidance rotorcraft missions based upon stored terrain map information.[2] In this system, and others involving stored information where guidance commands are generally continuous and change slowly with time, symbology can be presented to the pilot's HMD for manual command tracking. Because of insufficient accuracy in stored map information for flight below 300 ft radar altitude, automated terrain following and obstacle avoidance for NOE flight must be based upon real-time, line-of-sight, sensor information. This can result in highly dynamic and discontinuous guidance commands. In order to avoid excessive control workload as a result of a pilot attempting to process and track high frequency commands, automated fly-by-wire control authority is required of the PDG system. This requirement has important consequences for HMD symbology design.

HMD symbology for a highly automated NOE flight system is unique since it must provide pilots with navigation, flight-path direction, and system performance information while minimizing display clutter. Preventing display clutter is especially important at NOE altitudes in order to enable pilots to extract as much visual information as possible from the complex environment. The need for conformal symbology is also highly desirable when flying NOE. To provide conformality, provisions must be made to ensure that inertially referenced symbols are properly occulted with respect to terrain and obstacle features.

The purpose of this paper is to describe the function and mechanics of the HMD symbology developed for the automated NOE Pilot-Directed Guidance interface. Emphasis is given to describing the unique requirements for presenting conformal, inertially stabilized information to the pilot under NOE conditions. The paper concludes with important results, from data and pilot commentary, obtained from a recent fixed-base simulation, conducted on the NASA Ames Vertical Motion Simulator (VMS).

2. SENSOR REQUIREMENTS

In order to provide the HMD with heading, pitch, and bank attitude along with vehicle inertial velocity and position, an Inertial Navigation Unit (INU) will be required. To correct for drift errors in the INU and provide the high degree of positional accuracy required for NOE navigation, INU positional data will need to be augmented with lower frequency data from a Global Positioning System (GPS) sensor. In addition, a radar altimeter will be required to provide high accuracy, high bandwidth, above-ground-level (AGL) altitude information for the automated terrain following inherent in the PDG system.

Forward-looking on-board sensor information is required to provide terrain and obstacle information to the PDG guidance and control system. Forward looking sensors for obstacle avoidance are can be either active or passive, depending upon whether they emit energy. Passive forward-looking sensors, such as TV and Forward-Looking Infra Red (FLIR) are generally desirable for military NOE missions because of the high level of covertness that they provide. Limitations of such sensors include computational difficulties in extracting range information, inability to detect small obstacles such as wires due to lack of resolution, and operational difficulties in adverse weather conditions. For

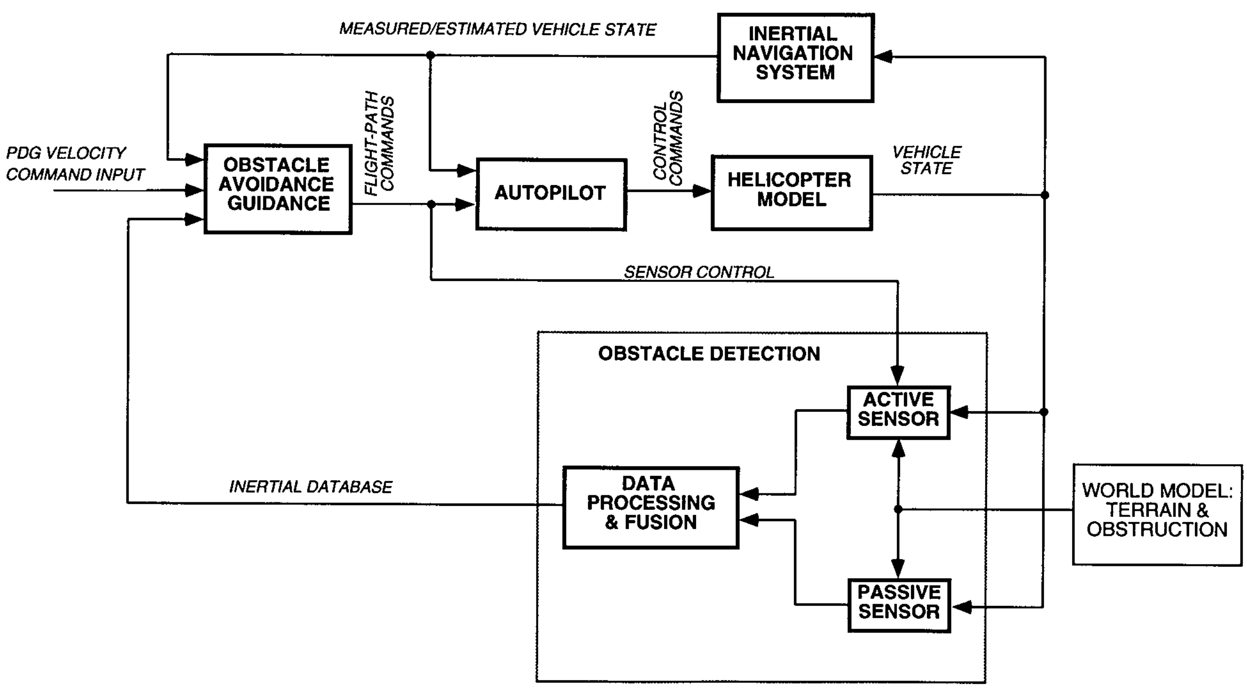

Fig. 1 Simplified PDG Guidance and Control System

these reasons, it is likely that an operational automated NOE system will include a narrow field-of-view active sensor, such as a laser range finder or millimeter-wave radar, in addition to a broader field-of-view passive sensor.[3]

The forward-looking sensor modeled in this simulation was a generalized, "perfect", sensor with a 60° x 60° field-of-view. The sensor was modeled with an angular resolution of 0.5° and an update rate of 2 Hz. To acquire rapid range information from the Computer Generated Imagery (CGI), a hardware range return buffer was utilized.[4]

3. HMD SYMBOLOGY

3.1 Display device

The Honeywell Integrated Display and Sighting System (IHADSS) was used to present HMD symbology to the pilot's right eye on a monocular lens attached to the helmet, as shown in Fig. 2. This system incorporated a display field-of-view of 40° horizontal by 30° vertical that was slewable up to a rate of 120°/sec with 120° of azimuth pointing angle range. Inertial stabilization of symbology was accomplished by an infra-red head tracking mechanism that allowed for compensation of pilot head movement in the pitch and yaw axes. Compensation in roll was not provided and therefore pilots were informed to avoid lateral head tilting in order to minimize display errors. The primary IHADSS PDG display symbology that resulted from the fixed-base VMS simulation is shown below in Fig. 3. The display includes a combination of screen-fixed and inertially stabilized symbology.

3.2 Nominal course information

Although not constrained by the PDG to flying a fixed course, pilots flying NOE are typically given some type of nominal course along which to fly in order to satisfy mission objectives. This course may be defined by a series of waypoints or it may be the result of a high-level path planning routine that includes terrain optimization and threat avoidance.[2] Regardless of how this course is defined, it will not typically have information regarding obstacles and micro-terrain features for which a sensor is required.

Early in the development of the PDG interface, pilots requested that nominal course information be presented head-up as well as on a panel-mounted moving-map display to facilitate the navigation task. Following extensive simulation development, pilots opted for the representation of nominal course information by a series of inertially fixed two-dimensional (2D) symbols resembling croquet wickets with slanting sides, oriented perpendicular to the waypoint course. Ten wickets were visible on the HMD, depending upon pilot head position, at any given time. The display was initiated by placing the first wicket symbol 160 ft ahead of the perpendicular projection of the vehicle on to the piecewise linear waypoint course. The remaining nine wickets were then placed ahead of the first, spaced by 50 ft intervals. The first wicket was removed, and a new tenth wicket added, whenever the projected vehicle position overflew the first wicket position. New wickets were spaced 5 seconds ahead of the previous wicket at the current groundspeed.

Pilots were informed that the wicket symbols were 20 ft wide at the top and 40 ft wide at the base. Knowing the size of the wickets with respect to the outside scenery provided an additional cue to pilots from which to judge obstacle clearances. The height of the wicket symbols was set equal to the commanded radar altitude, referenced to the skid height of the helicopter. Level flight at the commanded AGL altitude was then represented by the flight-path vector aligned with the horizon, offset from the tops of the wickets by the distance of the pilot's eyepoint to the skids of the vehicle. Pilots felt that display clutter was reduced with this approach since the horizon was not coincident with the tops of the course wickets when flying the commanded AGL altitude.

Vertical placement of wicket symbology conformal with the terrain was based solely upon stored terrain information. Terrain altitude at the computed horizontal coordinates for each wicket was interpolated from Level 1 Digital Terrain Elevation Data (DTED). Since, in simulation, the visual imagery is constructed from DTED, calculation of terrain altitude for inertial symbology placement from this data guarantees display conformality. It is recognized, of course, that this would not be the case in an operational environment due to the potentially large uncertainties in DTED information. Course wicket placement in an operational system would require either a more accurate terrain database and/or the inclusion of forward-looking sensor data.

3.3 Reference point

In addition to the course-delineating wickets, the pilot-controlled reference point, represented by the inverted triangular symbol in Fig. 3, was also inertially stabilized in the pilot's HMD through head tracking. The purpose of the pilot-controlled reference point was to indicate the pilot's velocity command input being sent to the automated guidance and control system. Automated obstacle avoidance maneuvers took place whenever a direct line of sight to the reference point was obstructed. The reference point cue was also used to tell the pilot where he could expect the vehicle to be at some time in the future, indicated by a reference point predictive time parameter τ_{rp}. Pilots were given the

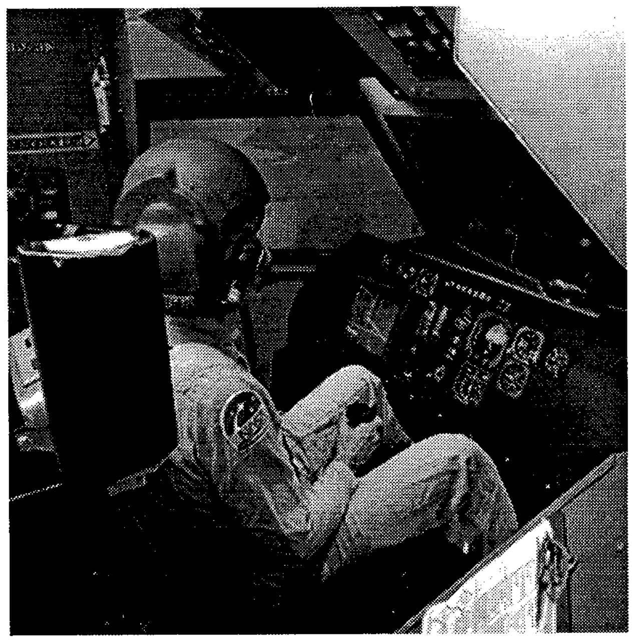

Fig. 2 Pilot with IHADSS

ability to vary τ_{rp} through longitudinal motions of a button on the cyclic grip. As shown in Fig. 3, τ_{rp} was presented digitally in the upper right of the display. The vertex of the reference point was positioned at the terrain height by the same method as the course wickets.

The effect of all pilot control inputs is indicated in Fig. 4. Longitudinal cyclic inputs were used to control rate of change of commanded airspeed with centered longitudinal cyclic resulting in commanded airspeed hold. A change in the distance of the reference point from the vehicle could therefore be accomplished by either an adjustment of τ_{rp} or a change in groundspeed brought about by a change in the commanded airspeed from the cyclic. The distance of the reference point from the vehicle was limited to 1000 ft to keep it within the sensor-derived, inertial database that was designed to extend 1150 ft in all directions from the vehicle. An attempt to drive the reference point beyond 1000 ft resulted in the automatic reduction in τ_{rp} needed to keep the reference point at this maximum distance. The pilot was alerted to an automatic reduction in τ_{rp} by the flashing of the reference point symbol and the τ_{rp} digital display.

Azimuthal position of the reference point with respect to the vehicle was computed proportional to lateral cyclic stick input. As shown in Fig. 4, azimuthal displacement was constrained by a maximum angle ζ, referred to as the lateral search domain. This angle ζ, a direct input to the obstacle avoidance guidance, was used to limit the search for lateral avoidance maneuvers.[5] Since the system would default into a vertical, contour flight path mode whenever the search for lateral avoidance options was exhausted, a change in ζ greatly affected the performance of the system. The

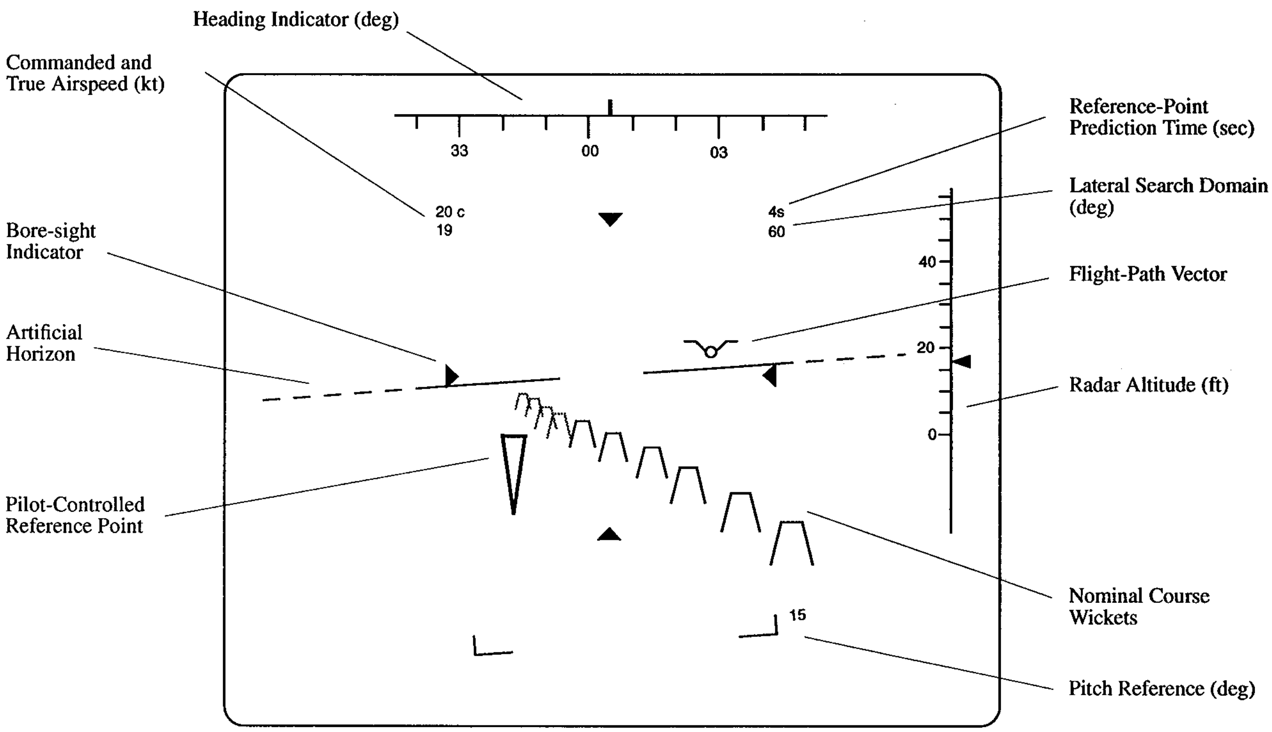

Fig. 3 PDG Helmet-Mounted Display Symbology

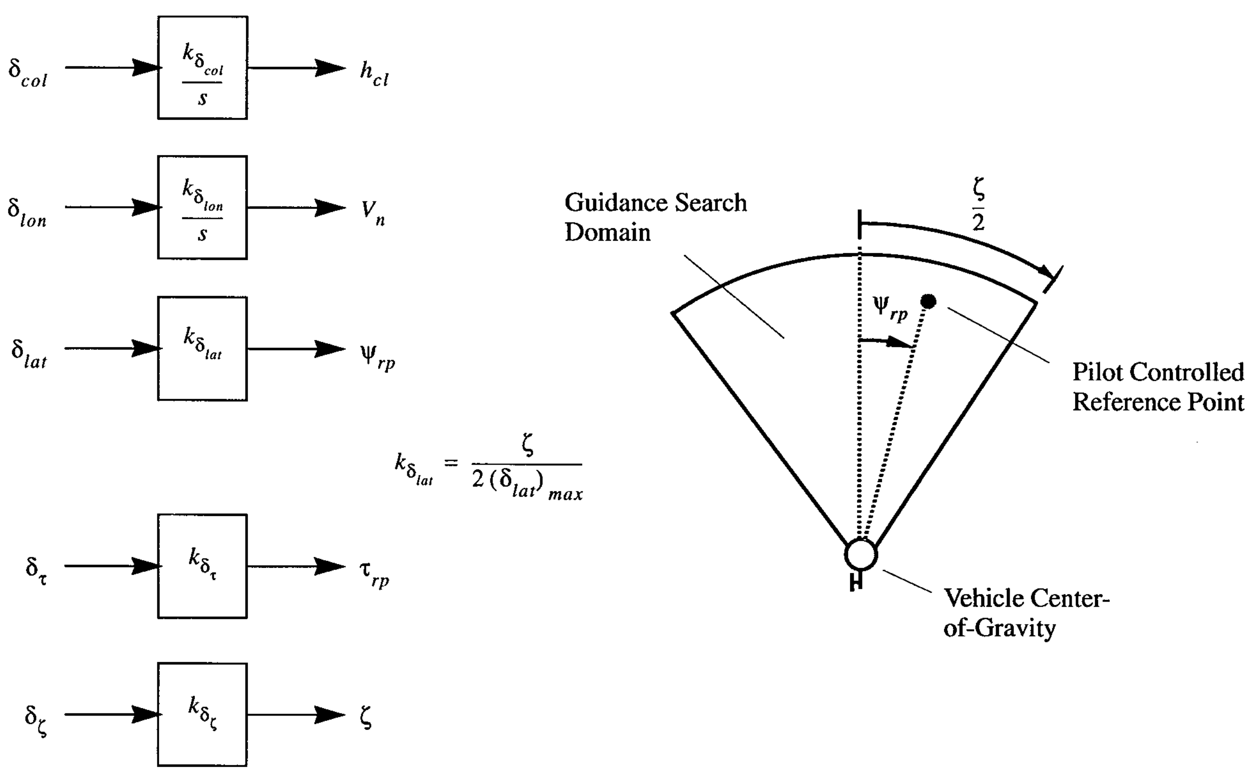

Fig. 4 Pilot-Directed Guidance (PDG) Interface

choice of ζ has been shown to be highly mission dependent, with larger lateral search domains selected for flights requiring a high degree of covertness and less emphasis upon time constraints. The PDG interface allowed for pilots to select an appropriate value for ζ through lateral motions of the cyclic trim-adjustment switch. The lateral search domain was presented digitally to the pilot in the upper right of the display, below the predictive time parameter. A variable gain was applied to the lateral cyclic input in order to place the reference point on the boundary of the lateral search domain when maximum stick displacement was applied.

Together with the maximum distance constraint, the lateral search domain of the reference point formed a 2D conical region wherein the reference point could be driven with respect to the vehicle. This region was presented on the moving-map display along with a cross-hair symbol showing the corresponding reference point position. The azimuth search domain was indicated on the HMD by two dashed "poles" drawn inertially 950 ft from the vehicle at azimuths of $\pm\ \zeta/2$ from the vehicle heading.

3.4 Flight-path vector and pitch ladder

The vehicle flight-path vector, represented by the gull-winged symbol in Fig. 3, was driven with respect to the nose (bore-sight) of the aircraft by angle of attack α, and sideslip β. In order to prevent pilot induced oscillation due to delayed response of vertical flight path vector to control inputs, a quickening term was added to the display law. The quickening was based upon collective (power) inputs rather than pitch rate due to the greater responsiveness of flight path vector to power changes at low airspeed. The compensated angle-of-attack was then given by

$$\hat{\alpha} = \operatorname{atan}\left(\frac{\hat{w}}{u}\right) \tag{1}$$

where u is the longitudinal body-axes airspeed, and $\hat{w}$ is vertical body-axes airspeed modified by a washed-out collective term, i.e.

$$\hat{w}(s) = w(s) - \frac{(Z_{\delta_c}/Z_w)\,s}{s - Z_w}\delta_c(s) \tag{2}$$

where Z_w and $Z_{\delta c}$ are the helicopter model sensitivities of vertical acceleration to changes in vertical airspeed and collective inputs respectively. In the case of PDG, where collective inputs are not directly coupled to the vehicle dynamics, δ_c refers to the collective perturbation about trim that was computed by the inverse aerodynamic model residing in the controller.

In order to smooth the compensated angle of attack for presentation on the HMD, $\hat{\alpha}$ was passed through a first order filter with a quarter second time constant, i.e.

$$\hat{\alpha}_d(s) = \frac{4}{s+4}\alpha(s) \tag{3}$$

At the very low airspeeds associated with NOE flight, the flight-path vector symbol becomes extremely sensitive to changes in vertical and lateral airspeed. This is especially evident in manual NOE flight where pilots are required to carefully regulate aircraft pitch and power in order to hold airspeed and height above terrain. To minimize this phenomenon, the longitudinal component of airspeed being sent to the flight-path vector display law was limited to a minimum 30 kt, resulting in a pseudo flight-path vector representation for speeds lower than this. Pseudo lateral and vertical flight-path vector with respect to the bore-sight of the aircraft, for speeds $0 \le V_t \le 30$ kt, was then given by

$$\beta_p = \frac{v}{u_{min}} \tag{4}$$

$$\hat{\alpha}_p = \frac{\hat{w}}{u_{min}}$$

where $u_{min} = 30$ kt.

Vertical, flight-path angle was indicated on the HMD by the position of the flight-path vector with respect to the inertially stabilized artificial horizon and pitch ladder. The azimuth of this symbology was fixed to the longitudinal axis of the vehicle, in response to pilot preference. The artificial horizon line was chosen to extend ± 45° off boresight. Pitch ladder information was presented in increments of 5°, beginning at ±15°. Pitch resolution below 15° magnitude was not considered important enough to pilots to warrant the associated display clutter.

3.5 Screen-Fixed Symbology

The screen-fixed symbology, i.e. symbology that remained at a fixed 2D location on the pilot's display despite head movement, included radar altitude, heading, and groundspeed information. The arrangement of the screen-fixed symbols in the PDG interface was similar to that developed for pilot monitoring of fully automatic NOE flight maneuvers.[7] Radar altitude information, as shown in Fig. 3, was presented by a sliding, vertical tape. True vehicle radar altitude was indicated by an open triangular pointer that remained fixed in the right-hand center of the display. For missions requiring precise commanded AGL altitude tracking, the commanded altitude was indicated by a closed pointer to the right of the sliding tape. Heading information was presented in a similar manner with a sliding tape oriented horizontally at the top of the display, where vehicle azimuth was indicated by a center-fixed pointer. Since heading information was available on the instrument panel as well as on the moving-map display, pilots commonly chose to de-clutter the HMD by removing the heading tape.

The remaining screen-fixed symbology consisted of digital information that included the predictive time parameter, τ_{rp}, and lateral search domain ζ, described previously, along with commanded and actual airspeed. Airspeed information was presented in the upper left of the display with the commanded speed presented above the true vehicle speed. As with all symbols on the HMD, this information could be removed for display de-clutter at the pilot's request.

4. OCCULTATION AND DEPTH CUEING

A primary requirement for the presentation of inertially referenced symbology is to provide the pilot with all the visual cues necessary for determining the correct three-dimensional position and orientation of symbols with respect to terrain and obstacles in the outside visual scene. This is an especially challenging requirement for flight at NOE altitude because of the complexity of the environment. Incorrect spatial interpretation of symbology by the pilot could potentially lead to guidance, navigation, and control errors that could have serious mission and safety consequences.

In the PDG simulation experiment it was necessary to represent the nominal course and pilot-controlled reference point accurately with respect to the terrain and obstacles in the Computer Generated Imagery (CGI). This required that symbols be properly occulted (i.e. hidden) where necessary by database features in order to provide the correct visual cues to the pilot. The initial approach considered was to partition each inertial symbol into segments and then perform a line-of-sight calculation to the geometric centroid of each element. Due to the impact on the desired update rate of 20 hz for the HMD symbology, it was decided to limit calculations to a single line-of-sight determination for each complete symbol. This calculation was performed within the sensor-derived inertial database by using a simple geometric ranging algorithm that returned range as a function of the symbol's azimuth and elevation angles in the vehicle body-axes.[8] Occultation was signified by a calculated range at the body-axes bearing of the symbol's centroid that was less than the known range to the symbol's desired position.

Two methods of representing symbol occultation were examined in the simulation. The first, which involved making occulted symbology invisible, was shown to seriously impact the continuity of the course-delineating wickets in the presence of obstacles. For this reason, pilots chose the second representation that involved displaying occulted symbology by dashed line segments. This method of display, which had the effect of making occulted symbols appear dimmer on the HMD, preserved course continuity and reduced the possibility of navigation errors. Occultation of the reference point, although determined in the same manner as the course wickets, was not generally noticeable since the automatic system would normally maneuver the vehicle to preclude the occurrence of intervening obstacles.

Occultation of the course wicket symbols with each other was also investigated in the simulation. The first approach involved non-occulting course symbols that were displayed as wire-frame entities. Due to the considerable display clutter and confusion resulting from this approach, it was decided to represent the course wickets as opaque 2D symbols so that proper occulting would occur on the IHADSS display. Furthermore, all of the non inertially-fixed symbology automatically occulted the course wickets and reference point whenever HMD coordinates coincided.

Brightness control of individual symbols according to importance and geometric distance was also found to significantly affect pilot opinion and interpretation of the HMD symbology. Elements of the display requiring relatively high pilot attention were made to appear brighter than those requiring less monitoring. To facilitate individual pilot preference, brightness control was made available on all HMD symbols. In general, pilots asked for the flight-path vector, pilot-controlled reference point, and pitch-ladder/artificial horizon symbols to be brighter than the radar altitude tape, heading tape, and digital information. In order to convey distance, the display intensity of the course posts was varied linearly from the first (nearest) post to the last (farthest) post, such that the first post was 5 times brighter than the last.

5. SIMULATION EXPERIMENT

5.1 Simulation experiment

Three NASA research pilots participated in the simulation experiment. It was conducted on the Ames fixed-base Interchangeable Cab (ICAB) facility incorporating three windows of Evans & Sutherland CT5A CGI. Trees were added to the CGI terrain database to provide a realistic and challenging NOE obstacle environment, as evident in Fig. 5.

The primary objective of this initial simulation was to gather flight-path performance and pilot workload data with which to evaluate the potential of the PDG obstacle avoidance concept. The test compared the flight performance of the PDG system in missions conducted at various airspeed and visibility conditions, with that of the non-automated helicopter. Three airspeed conditions (15, 20, 25 kt) and three visibility conditions (5000, 2500, 1000 ft) Runway-Visual-Range (RVR) were examined. All flights were conducted without winds or turbulence so that inertial and air referenced velocities were identical. Data runs were conducted in pairs by having pilots first fly a given set of airspeed and visibility conditions manually, followed by PDG. A single course of length 4 n.mi, defined by a series of waypoints, was used for all data flights. Pilots were instructed to attempt to conduct the entire flight at an AGL altitude between 10 and 45 ft. To provide a suitable balance between flight-path control and automatic maneuver aggressiveness, pilots typically chose to fly with a reference point-look ahead time between 3 and 5 seconds. The lateral search domain, although selectable from the cockpit, was held constant at 60° in order to provide comparable simulation results.

IHADSS HMD symbology was also provided for the comparative flights without PDG. For these manual flights, the symbology was identical to that used with PDG except for the absence of the pilot-controlled reference point and the addition of a lateral acceleration indicator ball at the bottom of the display.

5.2 Results

The data gathered during this preliminary simulation provided information on flight-path performance and pilot workload, with and without the PDG automation. The three most significant results were: 1) The PDG obstacle-avoidance system allowed flights to be conducted at a lower mean AGL altitude, thereby reducing the amount of time exposed above tree-top level. This was especially evident under poor visibility conditions. 2) The PDG automation improved flight safety by increasing obstacle clearances. 3) PDG resulted in a decrease of pilot-perceived workload, under all flight conditions tested.

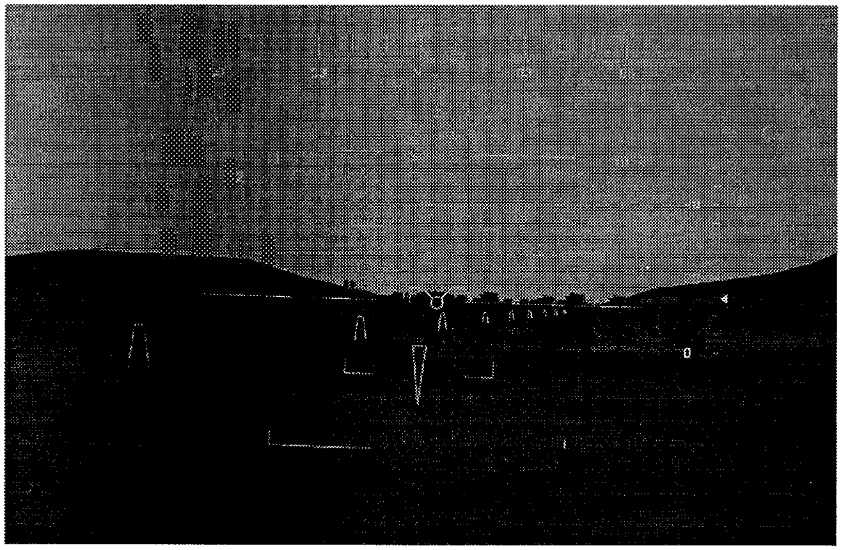

Fig.5 NOE Simulation Database

There were pronounced changes in the conceptual use of the PDG system and associated symbology as visual conditions deteriorated. Pilots stated that in adequate visibility (i.e. RVR $\geq$ 2500 ft) primary obstacle avoidance was performed manually by simply guiding the PDG reference symbol among obstacles. Given adequate visual range, flight-path planning for obstacle avoidance was performed well in advance of any control response from the automatic system. In this situation the PDG obstacle avoidance system was regarded as a secondary backup resource to ensure safety of flight. As visual range was decreased to 1000 ft RVR, however, pilots found it difficult to perform long range planning for obstacle avoidance and were therefore more dependent upon the PDG system for primary obstacle detection and avoidance.

Due to the loss of visual cues from the environment as visibility decreased, airspeed and altitude control, along with course navigation, became increasingly difficult. This resulted in a corresponding increase in the importance and utilization of the associated HMD symbology. A high degree of reliance upon HMD nominal course information was observed by pilots when flying at the low visibility level of 1000 ft RVR. Under adequate visual conditions, pilots routinely chose to deviate from the nominal course, delineated by the wicket symbols, to either facilitate long range obstacle-avoidance flight path planning or to reduce the flight time required in reaching an upcoming waypoint). At low visibility, however, pilots tended to avoid significant departures from the waypoint course in order to prevent from becoming lost or disoriented, despite head-down map information.

Unresolved symbology and display issues, observed in the simulation, concerned the presentation of true flight-path vector at low airspeeds and the communication of imminent automatic obstacle avoidance maneuvering. Prompting the implementation in Eq.(4) of a pseudo flight-path vector below 30 kt, the display field-of-view was found to be inadequate to represent true flight-path vector at the low airspeeds tested. Pilots also noted that forward information, in terms of symbology, would be desirable to indicate the direction and magnitude of impending automatic maneuvers resulting form the PDG guidance logic. An attempt to solve this problem during this initial evaluation proved unsuccessful due to the high bandwidth of the commanded velocity vector resulting from the discreet PDG guidance logic.

6. CONCLUSIONS

Helmet-Mounted-Display symbology, necessary in providing an effective pilot interface with an automated Nap-Of-the-Earth obstacle avoidance system, has been developed and evaluated in a piloted simulation. Although the simulation primarily concerned the performance characteristics of the Pilot-Directed-Guidance system rather than a strict, quantitative HMD evaluation, important NOE symbology design considerations were discerned. Pilots concluded that inertially referenced, course-delineating, symbology was acceptable in providing head-up navigational information while minimizing display clutter. HMD symbology depicting aircraft velocity, altitude, and heading information was also satisfactory in allowing pilots to perform the NOE task, with or without PDG automation.

The most notable pilot objection to the PDG system concerned the lack of advanced knowledge/warning of imminent automatic maneuvering. A means of communicating this information in an effective manner, either through symbology or other means (e.g. aural), remains a subject for further research. Although not addressed in this initial simulation, it is likely that pilot acceptability of automated NOE systems will require the presentation of sensed obstacle information to the HMD.[9] Such information would enhance situational awareness and provide for increased flight safety under all environmental conditions, irrespective of an automatic obstacle-avoidance control system. The presentation of this information in a clear and effective manner, while preventing display clutter, is another subject for further investigation.

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